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MODELING RECYCLABILITY: HOW CAN WE PREDICT THE EVOLUTION OF RECYCLING CHAINS?

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ABSTRACT

Sustaining the material basis of society is becoming increasingly complex as demand grows for ever more sophisticated materials. As concerns regarding material availability arise, many studies following material stocks and flows and defining material criticality are being conducted. These assessments provide information that can be decisive for the industrial deployment of sustainable and innovative technologies. Disruption risks to the supply chains must be predicted to prevent material shortages at the corporate, national and global scale. Designers can play a major role for the preservation of material resources by considering the evolution of material availability at the material selection stage. Bearing in mind the lifecycle of any product, material recyclability will progressively become a key factor for the design process. This paper is part of an on-going research being conducted at the G-SCOP lab of the Grenoble Institute of Technology, whose aim is to provide dynamic resource scenarios and additional input to Design for Recycling guidelines, so as to assist material selection in the design process. It presents a framework to identify the parameters that determine the evolution of recycling chains, based on material flow data and historical accounts of the shifts, ascent and decline of recycling activities. This should allow designers to incorporate material criticality and recyclability to their lifecycle assessments.

Keywords: recycling chains; recyclability; MFA; design.

INTRODUCTION

In the last 25 years, the array of materials synthesized in laboratories and present in industrial applications has expanded considerably. Not only has the economy become omnivorous in its consumption of elements from the periodic table [1], but scientists have also gone to great lengths to produce materials that are ever more sophisticated, complex and architected, down to the nano-scale. The advances in sectors such as carbon-lean energies, information and communication technologies have led to a steep increase in demand for materials whose reserves seem inadequate to fulfil future scenarios [2]–[4]. Yet, despite the economic and ecological need of preserving resources through recycling, by establishing what is called a closed-loop economy, most industries and material value-chains are still open-looped. This means that materials follow more complex routes and a wider range of end-of-life applications are currently in place. Today, material lifecycles look more like a spiral or a coil than a circle.

Even though research has been performed on recyclable materials and more efficient

recycling processes, secondary lifecycles in the industry are still commonly placed beyond the range of the design process. In order to promote product and material recycling, designers have compiled Design for Recycling (DfR) guidelines for more than two decades, yet these seem to “lack a combination of concrete instructions, prioritization, and recyclability performance feedback” [5]. In many cases, designers have little to no contact with the recyclers of their products. How is the loop to be closed if both ends never meet?

Recyclers have gathered decades of recycling experiences and there is enough data today to evaluate how – and above all why – recycling chains tend to become necessary and grow, stagnate or disappear depending on the social, economic, political and technological environment of their time. This information is capital to evaluate how designers' decisions affect the shape of material flows and meet the material needs that future technology will require.

This paper is part of an on-going research being conducted at the G-SCOP lab of the Grenoble Institute of Technology, whose aim is to provide dynamic resource scenarios and additional input to Design for Recycling guidelines, so as to assist material selection in the design process. It presents a framework to identify the parameters that determine the evolution of recycling chains, based on material flow data and historical accounts of the shifts, ascent and decline of recycling activities. This should allow designers to incorporate material criticality and recyclability to lifecycle assessments.

THE LINK BETWEEN AVAILABILITY, VALUE AND RECYCLABILITY

Addressing material availability in design

Designers are facing interesting times. They are expected to constantly provide technological innovations that enhance everyday life, improve production systems, create value and reduce environmental impacts. However, in their attempt to meet these expectations on a global level, a new constraint has surfaced: material scarcity. The increasing demand for manufactured goods and energy resources in developing markets in Asia, Africa and Latin America has led to an intensification of the consumption of commodities in general and some materials in particular. Many of today's information and communication technologies, as well as most carbon-lean energy systems, depend on materials whose future availability is uncertain at best. In their assessment of the risks to the supply chain associated with material availability, Alonso *et al.* [6] state that “over the long term, market forces and technology will effectively ensure that responses such as substitution and recycling will occur” in case of material scarcity or disruption. They also suggest that material selection decision-making is a means to develop a strategy to reduce vulnerability and mitigate material shortages.

Increasingly, mastering material sourcing will become a key issue for industries developing sophisticated materials for innovative products. The designer should consider the present and also future availability – and therefore value – of material supplies during the design process. Thus, it is crucial to address material availability and recyclability at the material selection stage, aiming for more efficient material uses and recovery at the end of the product's lifecycle.

Material value considerations

The value of a given material depends on several factors regarding supply and demand issues. Supply is defined by the raw materials' extraction and production processes. In the case of ceramics and metals, geological occurrence and concentration are key factors that involve geopolitical relations and may be a cause for concern in some cases,

especially when few countries possess the bulk of reserves. Mining activities also depend on long-term capital-intensive investments that are usually based on feasibility studies attempting to anticipate profitability and market fluctuations. Some ceramic materials and most metals are the by-products of the extraction of major carrier metals that constitute the ore and have less efficient processing rates. Price increases of these companion materials may encourage improved recovery of these materials. In the case of polymers, the fluctuations of fossil fuel reserves affect supply to the point that investments in plastic recycling and the so-called bio-plastics may be fostered or hindered depending on the rise and fall of oil prices.

In terms of demand, Binder *et al.* [7] have indicated that metal use increases with income growth, a statement that could be generalized to other commodities such as ceramics and polymers. Thus, since global population and economy are growing, one could consider the consumption of some materials as ever expanding in the near future [8]. This may not be true in some cases, where predictions have shown it may saturate [9]. Furthermore, adding a note of unpredictability to the mix, the very own innovation process can disrupt any forecasting model of demand, as technological innovations relying on new materials can quickly transform the demand of little-known, undervalued elements of the periodic table into overnight industrial favorites [2].

Recycling issues

Recycling has therefore become a strategic issue due to the realization of the intrinsic value of materials, to the point that urban mining – as recycling is now referred to – is considered an alternative to conventional mining. For instance, data from recyclers has shown that the concentrations of precious metals such as gold, platinum, palladium and silver, along with other metals such as copper, aluminium, iron, tin, nickel, gallium and germanium, present in current electric and electronic equipment waste, are superior than the concentrations of these metals in the virgin ores [10]. However, not every available metal is being recovered from Waste Electrical and Electronic Equipment (WEEE) as flows are still being mustered.

Recycling is hampered by a number of factors related to the management of waste flows as well as to intrinsic properties of the materials themselves. Usually, profitability, and therefore viability, of material recycling is considered to be relatively poor, which, added to the volatility of recycled material prices and the competition with original raw materials, makes investing in recycling operations a high-risk venture [11]. Recycling is not always viable depending on the material's applications. While some uses are both technically and economically feasible, others can involve recycling technology that may not be profitable yet due to lack of reserve waste volumes or waste prices. In some cases, recycling is inherently not feasible due to material dissipation during the lifecycle. Moreover, recycling operators often struggle due to lack of expertise for managing complex inputs from end-of-life streams, since the technological, economic and thermodynamic knowledge required to process waste is not the same as the one required for processing raw materials and ore [12].

In literature, there are several definitions of recyclability. In broad terms, recyclability could be defined as the ability of a material to be managed at the end of its lifecycle, collected, treated and re-enter the value chain, in an open or closed loop. For Villalba *et al.*, “recyclability is the ability a material has to reacquire the same properties it originally had” [13]. Peters *et al.* assume a designer's point of view and define recyclability as “the affordance a product has for recovering as much components and materials as possible (quantity) with the highest possible purity (quality) by the least amount of effort (ease) with existing recycling technologies” [5]. The French ADEME/AFNOR BPX30-323 environmental labeling guidelines define recyclability by either the recycled content of a given material in the products it is made with, or the recycling rate at the end of life, depending

on the maturity of the recycling market: in mature cases, for which most scrap is recovered and recycled, the recycling rate is considered, whereas in developing recycling markets, the reward goes to products that contain secondary material, so as to encourage these burgeoning activities [14]. Both cases assume a more practical point of view, based on actual data from the return of materials in industrial cycles. Yet the recycled content approach is still disputed for being “highly dependent of the system conditions, export share, growth and the existing open loop recycling practice”[15]. Mizuno *et al.* state that although DfR guidelines propose a theoretical calculation of the recyclability rate as “an expectation value of a rate of recyclable materials to total weight of the product at the design stage”, the recyclability rate of most products depends on a number of factors such as “legislation, economic situation, corporate policy, recycling technology, recycling processes, etc” [16].

Several recyclability rates are used in different contexts so as to better convey the potential recycling of materials but most of them circumvent the contextual information and are more interested in the present-time, practical and static value of the recycling rates rather than in understanding their dynamics. While they are useful for policy-making purposes, these indexes provide no information as to how the secondary material is employed, whether there is potential for improving these rates and if a closed-loop is attained or attainable.

FRAMEWORK FOR STUDYING THE EVOLUTION OF RECYCLING CHAINS

Scope delimitation

Materials differ in their flows, history and context so that each material has its own specificities. Nevertheless, some materials share the same qualities and can be compared to a certain degree, especially inside material classes. This comparison is interesting to obtain the factors that characterize anthropogenic cycles as a whole and those that are intrinsic to given material properties. The more chains are analyzed, the more parameters are considered, and the more general the model may be. However, it would be impracticable to provide a theoretical model of recyclability based on the evolution of availability for all materials. Therefore, the study will concentrate on metals, since they possess a larger information database and have some of the most developed, mature and well-recorded recycling chains.

Critical materials

Recent concern about material shortages has led to the emergence of studies on critical materials, i.e. materials whose supply disruption risks and economic importance are particularly disquieting. Because many of these materials are necessary for the large-scale deployment of strategic technologies for the near future (carbon-lean energy systems, information and communication technologies), predicting their demand and the vulnerability of the respective systems to fluctuations in supply can be decisive to ventures and their success in the long-run. Even though critical material listings vary according to the methodologies used in their assessment, they generally include rare-earth elements, the platinoid family, as well as specialty metals such as indium, scandium, tungsten and yttrium [4]. Avoiding the dissipative uses of these materials and securing their availability by fostering their recycling is the focus of many studies [17]–[22]. In their proposition of a methodology for metal criticality determination, Graedel *et al.* [21] suggest the relevant material characteristics for evaluating criticality in a temporal perspective, according to the organizational levels, as shown in Table 1. Clarifying the context, timeframe and assessment method is fundamental to any attempt at an assessment of criticality, as well as stakeholder validation and accounting for uncertainties through sensitivity analyses [4].

Table 1: Relevant material-related characteristics for different organizational levels [21]

	Using corporation	Using nation	Global
Focus	Relevance to that firm's product line	Relevance to national industry and population	All uses of a material, wherever they happen
Time scale	1-5 years	5-10 years	10-100 years
Supply potential	Crucial	Very important	Very important
Technological change	Very important	Worth consideration	Impossible to predict
Geopolitical factors	Crucial	Important	Unimportant
Social factors	Moderately important	Very important	Unimportant
Environmental implications	Important	Important	Moderately important
Intensity of competition	Crucial	Depends on national industry composition	Unimportant

Material flows into the end of life

Following the flows of materials in society is the first step in establishing a model for material availability and understanding the dynamics that drive material cycles. The main tool used in these studies is Material Flow Analysis (MFA) and, more recently, Dynamic Material Flow Analysis (DMFA). MFA is considered a fundamental industrial ecology tool and has many applications due to its very synthetic display of an element's – or substance's, in the case of Substance Flow Analysis – transformations and exchanges in society or with the environment. It provides a quantitative partitioning of a material in its different life stages for a given region or time period and may serve as a solid basis for sustainability assessments [23], [24], urban planning [25]–[27] or policy making [28]. When performed on a local level, they offer information on the social mechanisms of management systems and the economic interactions with neighboring regions, whereas analyses performed on a global scale – usually collected from several more local studies – portray general tendencies for material consumption and scarcity [29]. The general model for a MFA is presented in Figure 1.

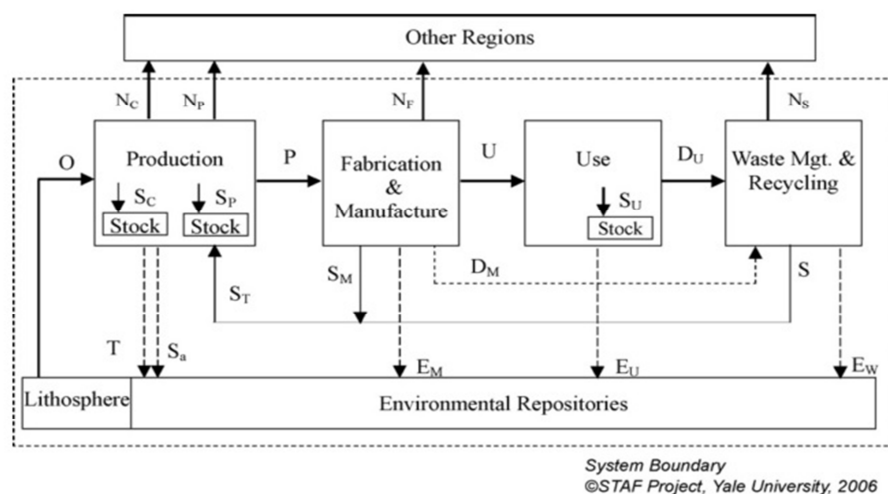


Figure 1: MFA general model [30]

To the general purpose of the research presented here, MFA is essential to quickly access an important volume of data, compiled in a comprehensive manner that quantifies primary and secondary material production, stocks in the economy according to the applications therein, different waste management strategies as well as material dissipation. Several MFAs have already been conducted, constituting an extensive albeit not exhaustive database. Many studies exist for specific materials, regions and timeframes and some attempts at an exhaustive inventory have been undertaken such as the Stocks and Flows Project led by Prof. Graedel from the Center for Industrial Ecology at the Yale School of Forestry and Environmental Studies, which has been studying the anthropogenic cycles of metals.

However, the MFA database is still incomplete and, although studies exist for hazardous chemical substances [31], plastics [32] and building materials [25], it is quite concentrated on metal cycles. Most analyses are also focused on developed countries, perhaps due to information availability and reliability as the flows in these areas are generally more controlled and formally registered. Most MFA studies are static and contained within a given region and timeframe, even if dynamic models are increasingly available.

One can extract from the mass balances indexes that characterize each stage of the lifecycle, such as those presented in Table 3. These coefficients allow the comparison between MFAs in regards to different timeframes, nations or materials. They also provide information on trends in the configuration of the material flows and can be used to validate claims made by the stakeholders on the evolution of the material's lifecycle, particularly in the end of life.

Table 3: Lifecycle coefficients obtained from MFA (¹: coefficients proposed by [33])

Production efficiency	$\rho = 1 - \frac{S_A + T}{O}$
Utilization efficiency ¹	$\psi = 1 - \frac{E_M + D_M}{U}$
Accumulation ratio ¹	$\alpha = \frac{S_U}{U}$
End of life recycling ratio ¹	$\zeta = \frac{S_T - S_M}{D_U + D_M}$
Secondary supply ratio ¹	$\theta = \frac{S_T}{P}$
Discard management ratio ¹	$\mu = \frac{D_M}{D_M + E_M}$

But, MFA is a lifecycle assessment tool that usually presents the material's lifecycle in broad strokes and is not very adapted at a micro-level [28]. Moreover, static and dynamic MFAs provide little to no contextual information and authors generally infer the circumstances that have shaped the flows and hypothesize their interpretations. To complement and confirm the inferences from the MFA, a comparison with historical data is needed. A look back to the origins of the material flows, and particularly of their end-of-life management, can clarify which contextual elements have an influence on the anthropogenic cycle and, ultimately, the availability of a given material. Stakeholders such as government agencies, eco-organisms, waste collectors and recyclers are a qualitative source of information that can provide empirical information from the industry. Associating the evolution of material availability with the history of recycling chains will point out the factors that determine recyclability.

This study will use Material Flow Analysis (MFA) as a primary source of data and historical records of recycling chains from literature and stakeholders as a guideline to in-

interpret the evolution of the material flows. Comparing the information from MFAs and the general context is what will allow the establishment of correlations between the parameters of the recycling chains' evolution and serve as the basis for a model of recyclability. Once it is finished, the model will be a synthesis of both quantitative and qualitative data, allowing the designer to address disruption risks to the supply chain, identify the need for substitution and conceive methods to prevent material dissipation.

PRELIMINARY REMARKS

The objective of this research is to provide a tool for designers to consider material availability when developing a product. Examining whether a material will be available in the future amounts to evaluating its criticality. Indicator-based methodologies for metal criticality determination already exist (Table 4). Nevertheless, recyclability is not a consequence of criticality exclusively. A designer considering the use of a material qualified as critical could be positioned both in the context of his corporation and his nation, as shown in Table 1, rendering concerns about supply potential, technological change, geopolitical and social factors, environmental indicators and the intensity of competition, primordial to the selection of a material. These assessments should be prepared based on projections made on a 5 to 10 years span, which corresponds to both the corporate and national timeframes of Table 1, since the designer is subject to his company's commercial interests as well as his countries social demands, economic policies and legislation. Although the global perspective is important for the long-term sustainability of the planet's biosphere and technosphere, its governance depends on the adoption of an international natural resources management policy, whose enforcement and governance conditions are beyond the scope of this study.

Table 4: Components of material criticality (adapted from [21])

Supply risk	Depletion time Companion metal fraction Policy potential index Human development index Political stability of suppliers Global supply concentration
Vulnerability to supply restriction	Economic importance of material Ability to pass through cost increases Social and economic permeability of material Substitute performance Substitute availability Environmental impact ratio Price ratio Corporate innovation

If a material is deemed as having a relative risk in being sourced, some alternatives are possible such as enhanced dematerialization, material substitution or a closed loop of a given strategic component. However, substitution is not always possible due to the lack or poor performance of a substitute, as is the case of magnesium, manganese, yttrium, rhodium, rhenium, thallium, lead, europium and dysprosium [34]. And though primary and secondary production of metals are based on similar hydrometallurgical or pyrometallur-

gical processes, recycling is still hampered by a lack of technical optimization [12].

The information from the MFAs and the bibliography covered so far are not conclusive and need confirmation from historical and practical data, field experts and stakeholders. This should also provide data on the secondary cycles in case of downcycling or upcycling. Stock balances are an important source of information and provide parameters such as primary source availability, primary over secondary production ratios, as well as import and export rates. DMFAs will be used to forecast the evolution of materials because they have the advantage of presenting trends by using life-span distributions to estimate derivative data from material flows.

There is a clear distinction between theoretical recyclability and practical results from WEEE chains, of up to 35% [16]. A 100% recyclability rate in theory does not entail in complete recovery of material. Connecting information from actual end-of-life chains with flow data can improve DfR guidelines but the criteria must account for context and product type. The preliminary parameters identified to constitute the model can be gathered into the following categories: geopolitical, economic, social/legislative, technological and logistical.

FUTURE WORK

The research will focus primarily on metals, since the MFA database is larger for this class. A probable distinction will be made among ferrous, non-ferrous, precious and specialty metals, though the latter encompasses a very broad spectrum of materials and properties and is a more heterogeneous group.

The interactions and relative impacts of each parameter will be equated and compared to the historical and present day scenarios in order to validate the model. Since the MFA database is quite varied in terms of materials, timeframes and regions covered, a general model is still distant and most hypotheses will be confirmed or disallowed by examining the experts' interviews. This will fill an important gap in the comprehension of how recycling chains evolve, since there are very few wide-ranging compilations of data describing the history of the recycling processes and industry in literature.

The integration of MFA in the design process will be detailed, especially in regards to its quick provision of information from the economy and its potential uses as a lifecycle assessment method. This approach should constitute a practical decision-making tool for material selection in design. Because material cycles are closely linked with product lifecycles, a case around WEEE will be studied to verify the applicability of the tool developed from this project.

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